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FINAL REPORT: PART 4

CONSTITUTIVE MODELLING OF JOINTS UNDER CYCLIC LOADING

PART 4: DEVELOPMENT OF SIMULATED ROCK LIKE MATERIAL AND TESTING

Submitted to

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PREFACE

This part contains brief description of development and testing of simulated rock type material that can be used in place of concrete. The need for this research was identified at later stages of this research project (AFOSR-830256) because the accuracy of measurements of deformation for concrete was limited due to its high stiffness, and damage due to cycles of loading was not significant. It is planned to use this material for future testing for rocks and rock joints.

This report, which constitutes a paper in the ASME Energy Technology Conference, Houston, Texas, 1989, also contains a study of the effect of specimen height on damage and softening in the material with respect to the hierarchical damage model proposed and developed during the project.

EFFECT OF SPECIMEN SIZE ON PROGRESSIVE DAMAGE AND SOFTENING IN SIMULATED ROCK

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ABSTRACT

It has been shown previously that the damage accumulation and resulting strain-softening behavior of geologic materials can be modelled by introducing a damage parameter, r, in the hierarchical approach of constitutive modelling. This parameter r, which is a function of deviatoric plastic strain trajectory, varies from zero for no damage condition to unity for maximum damage. Effects of sample size such as diameter and height in laboratory tests on the value of r have not been fully understood. In this paper, the effect of the height of the specimen on the damage parameter is investigated.

It is necessary to study the effect of sample size on progressive damage and strain-softening. Thus in the hierarchical model, it is appropriate to examine the effect on the damage parameter r. In this study, attention is restricted to laboratory tests with cylindrical specimens in which the diameter D = 3.0 inch (7.62 cm) specimen is maintained constant, while the height is varied. Since it is difficult to carry out this experimental investigation on real rocks, a rock-like material is simulated from a mixture of plaster of paris, cement, sand and water. This simulated

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rock shows damage accumulation and strain-softening characteristics similar to those of real rocks. This study would be able to identify effect of specimen height on damage in the existing plasticity based constitutive model.

INTRODUCTION

Geologic materials such as rock, concrete and soils exhibit inelastic nonlinear response. The phenomenon called 'strain softening' is reported in either uniaxial or triaxial compression at constant axial strain rate. Strain softening can be described as the decrease of strength during progressive straining after a peak strength value is reached.

Strain softening is not a true material property of rock, concrete or soil [1, 2] treated as continuum. If strain softening is a true continuum material property, various anomalous conditions may arise with respect to solution of boundary and initial value problems [3]. These anomalies can lead to loss of uniqueness in the softening part of the stress-strain response [2, 4].

Strain softening is a performance of structure (e.g. a finite sized specimen) in which the individual components such as microcracks, joints and interfaces result in an overall loss of strength with progressive straining [1, 2, 5-9]. It is obvious that the development of a model considering all the structural changes (e.g. microcrack propagation) in detail may not be easy to obtain. However, it is possible to model the average influence of the structural changes, and the strain softening model in the hierarchical approach has been established [10-13].

For the damage model, δ_{o+r}, in the general hierarchical approach, behavior of an element (specimen) is decomposed into two parts. The first part with volume V_t represents topical (continuum) behavior, which is non-softening and obeys an elastoplastic constitutive law. In the second part, which refers to the damaged or fractured part with volume V_o, the behavior is such that its shear stiffness is assumed to be zero. At every finite material element, therefore, the total volume is $V = V_t + V_o$. The damage parameter r is defined as

$$r = V_o/V \quad , \quad 0 \leq r \leq 1 \tag{1}$$

Experimental results have shown that there is no significant damage modification (accumulation) during unloading, so for the model at this time, the damage parameter r does not change during unloading. Since it is assumed that no damage is accumulated for (initial) hydrostatic compression, damage parameter r is expressed as a function of deviatoric plastic strain trajectory, ξ_D, as

$$r = f\ (\xi_D) \tag{2}$$

where

$$d\ \xi_D = (de^p_{ij}\ de^p_{ij})^{1/2} \tag{3}$$

and

$$e^p_{ij} = \varepsilon^p_{ij} - \frac{1}{3}\varepsilon^p_{kk}\ \delta_{ij} \tag{4}$$

The following expressions for r have been proposed [11]:

$$r = r_u \left(1 - \exp\left(-k\, \xi_D^{\,R}\right)\right) \tag{5}$$

$$r_u = 1 - (\sqrt{J_{2D}})_{res} / (\sqrt{J_{2D}})_{peak} \tag{6}$$

$$r = 1 - (\sqrt{J_{2D}}) / (\sqrt{J_{2D}})_{peak} \tag{7}$$

where k and R are damage related dimensionless parameters, r_u is determined from (shear) tests, the subscript "res" indicates residual stress level and the "u" indicates ultimate conditions.

However, the experiments have shown that the damage accumulation and hence the strain softening, is affected by the size of (cylindrical) specimens in the axial strain controlled compression tests [1, 14]. Hence, it is necessary to investigate the realistic relation between the damage parameter r and the sample size. In the original derivation of reference [11] the sample size effect on the damage parameter r was not included, and hence k and R in equation (5) are independent of the specimen size. The main purpose of this investigation is to seek a relation between k, R and the length of cylindrical specimens having a constant diameter. In order to identify the effect of changing diameter, additional tests and analysis will be needed.

EXPERIMENTS

A series of axial strain control unconfined compression tests were conducted on MTS machine available in the Constitutive Modelling Laboratory at the University of Arizona. Five cylindrical specimens with a diameter of 3.0 inches (7.62 cms) and heights of 2.0, 3.0, 4.0, 5.0 and 6.0 inches were made from a simulated rock like material. After several trials with different combinations of materials it was found that the following mix possesses stress-strain response similar to rocks but with much lower ultimate strength. This material which is termed as the simulated rock is composed of 62.5% sand, 8.3% cement, 12.5% plaster of paris and 16.7% water by weight.

A total of fifteen specimens were prepared, three specimens for every height. Results presented here are the average of three experiments conducted on each set of specimens. Figure 1 shows the $\sqrt{J_{2D}}$ as a function of ξ_D, where J_{2D} is the second invariant of deviatoric stress tensor. Now the variation of the damage parameter r with ξ_D can be obtained by using equation (7) and the experimental results in Fig. 1. Variation of r as a function of ξ_D for different specimen heights are plotted in Fig. 2. It can be seen that the development of damage and the rate of softening are affected by the height of the specimen. It is interesting that the ultimate softening appears to be similar in all cases. These results are in agreement with the observations of Read and Hegemier [1] for height/diameter (h/D) ratio greater than 0.5. However, for h/D less than 0.5, the specimen will experience increasingly lesser damage and softening.

DEPENDENCE ON SPECIMEN SIZE OF PARAMETERS:

Figures 3 and 4 show variations of k and R with specimen height. The values of k and R are obtained by fitting equation (6) in a least square sense to each curve in Fig. 2. In these calculations, as an approximation the value of r_u is adopted equal to unity. In addition, r_u in equation (6) is a factor so that this assumption does not introduce any significant error in the computation of k and R variation with the sample size. The k and R values, thus obtained, show a monotonically increasing nature with the height of the specimen as shown in Figs. 3 and 4. Figure 3 indicates that k is dependent significantly on the height, while R is less sensitive to the height, Fig. 4.

CONCLUSIONS

Geologic materials such as rock, sand and soil exhibit strain softening phenomenon which is caused by structural changes and damage. It is found that damage is dependent on the size of the specimen. In this limited study, the effect of specimen height on damage and damage parameters in the proposed elastic-plastic model is studied. Additional research will be needed to consider effect of specimen diameter.

Once the effect of specimen size is defined, the proposed model can be used for solution of boundary value problems involving damage and strain-softening.

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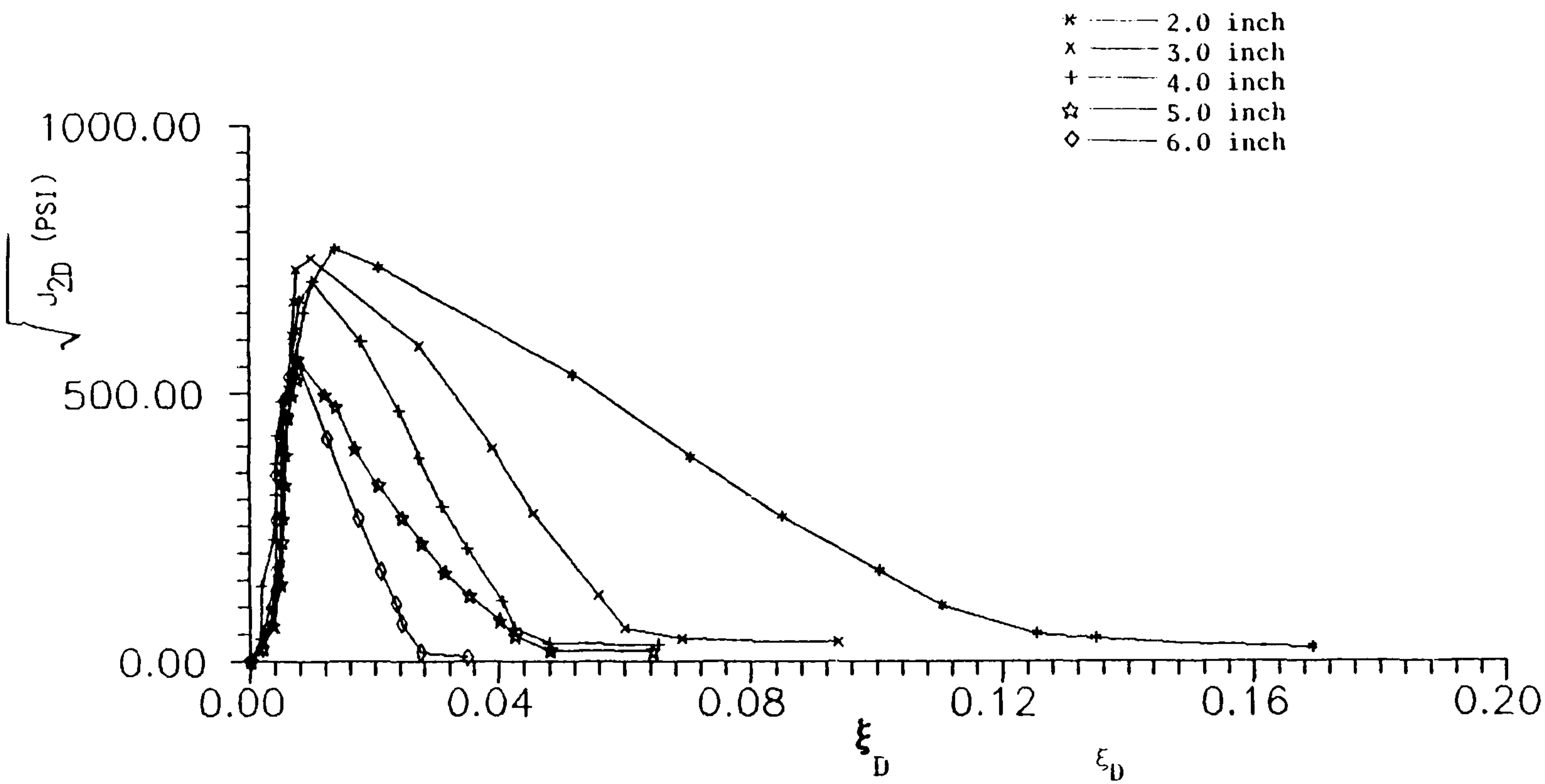

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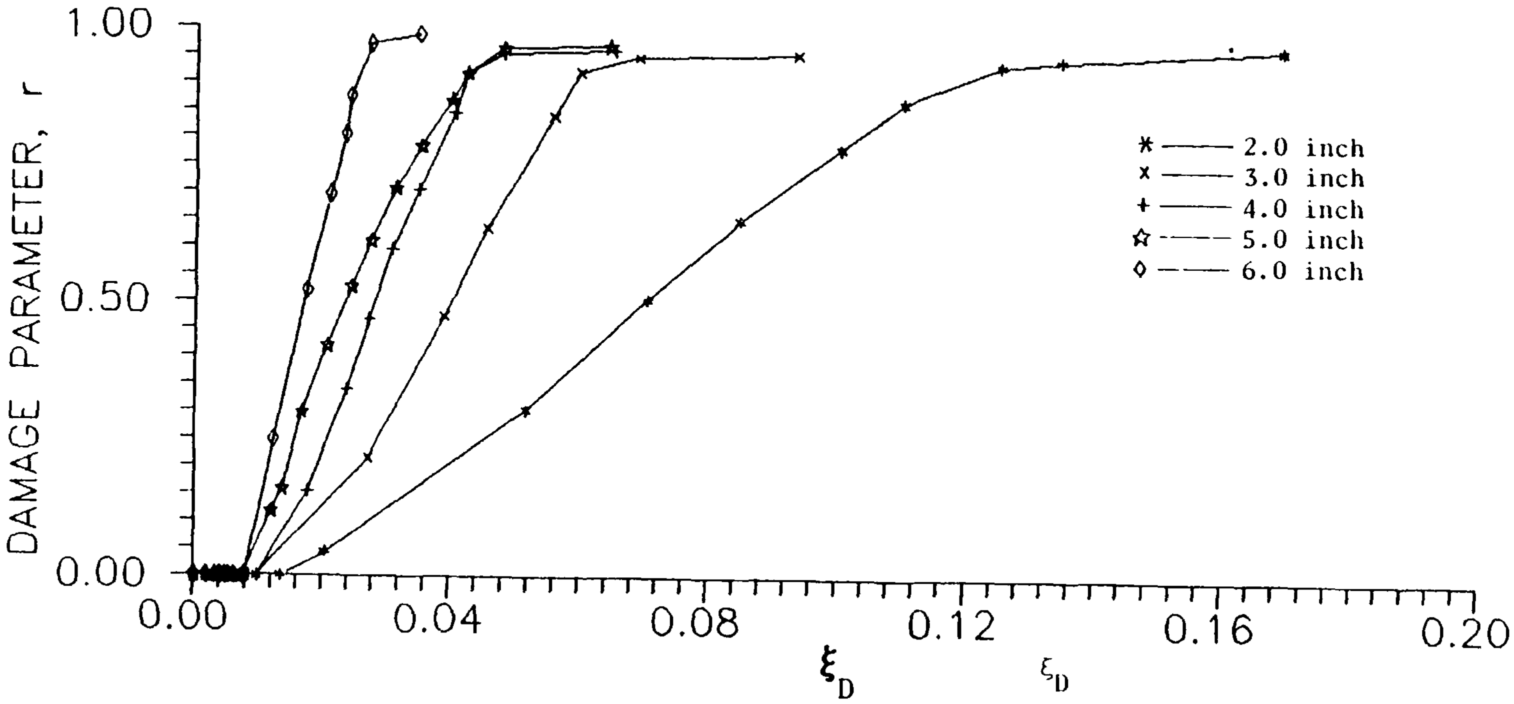

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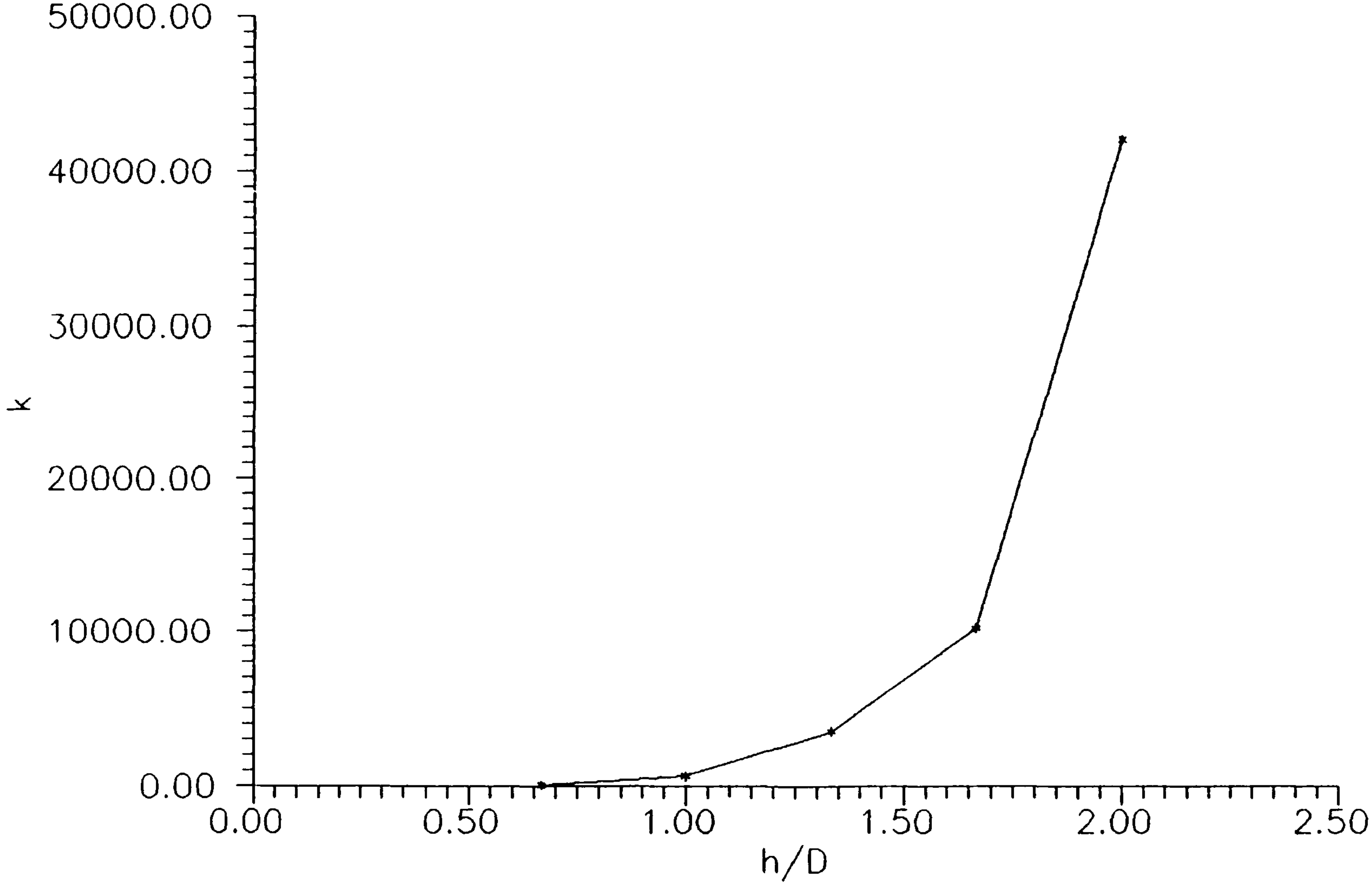
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Fig 4